# Claims

[c1] What is claimed is:

1.A method for characterizing a subsurface formation, comprising the steps of:

disposing within a borehole a logging instrument equipped with at least first transmitter and receiver antennas spaced apart by a first distance, at least one of the first antennas having a tilted magnetic dipole with respect to the longitudinal axis of the instrument, the antennas being oriented about the axis of the logging instrument such that the at least one tilted magnetic dipole corresponds to a first azimuthal angle;

azimuthally-rotating the logging instrument within the borehole;

while the logging instrument is rotating, activating the first transmitter antenna to transmit electromagnetic energy into the formation;

while the logging instrument is rotating, directionally measuring the first voltage signals associated with the transmitted electromagnetic energy using the first receiver antenna, as a function of the azimuthal orientation of the logging instrument, so as to determine the azimuthal variation of the measured first voltage signals;

and

fitting the azimuthal variation of the measured first voltage signals to approximate functions.

[c2] 2.The method of claim 1, wherein the fitting step is executed while the first voltage signals are being measured.

[c3] 3.The method of claim 2, further comprising the step of stopping the fitting when convergence has been achieved.

[c4] 4.The method of claim 3, wherein the activating, measuring, and fitting steps are repeated to execute subsequent acquisition cycles.

[c5] 5.The method of claim 1, wherein the fitting functions are sinusoids defined by coupling components of the first transmitter antenna"s magnetic dipole and first receiver antenna"s orientation vectors.

[c6] 6.The method of claim 5, wherein the coefficients of the fitting components are functions of earth formation parameters including at least one of resistivity of formation beds, location of the logging instrument, borehole deviation, azimuth angle at the location of the logging instrument, and a combination thereof.

[c7] 7.The method of claim 6, wherein the fitting coefficients

include constant, $\sin\Phi$, $\cos\Phi$, $\sin 2\Phi$ and $\cos 2\Phi$ terms that define an iterative fitting algorithm useful for determining the azimuthal dependence of the directional measurements.

[c8] 8.The method of claim 7, wherein the iterative fitting algorithm is used for selected real-time directional measurements having utility in geosteering.

[c9] 9.The method of claim 1, where the fitting coefficients are determined using a Fast Fourier Transform.

[c10] 10.The method of claim 1, wherein the logging instrument is further equipped with second transmitter antenna and receiver antennas spaced apart by the first distance, the second transmitter having a magnetic dipole whose tilt corresponds to the tilt of the first receiver antenna and the second receiver antenna having a magnetic dipole whose tilt corresponds to the tilt of the first transmitter antenna such that at least one of the second antennas has a tilted magnetic dipole, the second transmitter and receiver antennas being oriented about the axis of the logging instrument such that the at least one tilted magnetic dipole corresponds to a second azimuthal angle, and further comprising the steps of:
while the logging instrument is rotating, activating the second transmitter antenna to transmit electromagnetic

energy into the formation;
while the logging instrument is rotating, directionally measuring the second voltage signals associated with the transmitted electromagnetic energy using the second receiver antenna, as a function of the azimuthal orientation of the logging instrument, so as to determine the azimuthal variation of the measured second voltage signals;
fitting the azimuthal variation of the measured second voltage signals from the second receiver to approximate functions.

[c11] 11.The method of claim 10, wherein the second azimuthal angle differs from the first azimuthal angle by substantially 90 degrees.

[c12] 12.The method of claim 10, wherein the second azimuthal angle is substantially equal to the first azimuthal angle.

[c13] 13.The method of claim 10, wherein the fitting step is executed while the second voltage signals are being measured.

[c14] 14.The method of claim 13, further comprising the step of stopping the fitting when convergence criterion has been achieved.

[c15] 15.The method of claim 14, wherein the activating, measuring, and fitting steps are repeated to execute subsequent acquisition cycles.

[c16] 16.The method of claim 10, wherein the fitting functions are sinusoids defined by coupling components of the first transmitter antenna"s magnetic dipoles and first receiver antenna"s orientation vectors, and by coupling components of the second transmitter antenna"s magnetic dipoles and second receiver antenna"s orientation vectors.

[c17] 17.The method of claim 16, wherein the coefficients of the fitting components are functions of earth formation parameters such as resistivity of formation beds, location of the logging instrument, borehole deviation, and azimuth angle at the location of the logging instrument.

[c18] 18.The method of claim 17, wherein the fitting coefficients include constant, sinΦ, cosΦ, sin2Φ and cos2Φ terms that define an iterative fitting algorithm useful for determining the azimuthal dependence of the directional measurements.

[c19] 19.The method of claim 18, wherein:
the measured first and second voltage signals are complex voltage signals; and

further comprising the steps of:
calculating the phase-shift and attenuation values from the fitting coefficients for the measured first and second voltage signals;
combining the calculated phase-shift and attenuation values for the measured first and second voltage signals to generate a symmetrized or anti-symmetrized measurement.

[c20] 20.The method of claim 19, wherein the combination of calculated phase-shift and attenuation values is achieved by one of a sum and a difference.

[c21] 21.The method of claim 18, wherein:
only one of the first antennas has a tilted magnetic dipole; and
further comprising the step of:
characterizing the noise of the measured first and second voltage signals using the second harmonic coefficients.

[c22] 22.The method of claim 18, wherein:
each of the first antennas has one of a tilted and a transverse magnetic dipole; and
the fitting coefficients include third harmonic coefficients; and
further comprising the step of:

characterizing the noise of the measured first and second voltage signals using the third harmonic coefficients.

[c23] 23.The method of claim 18, further comprising the step of characterizing the noise of the first and second measured voltage signals by combining the first and second measured voltage signals.

[c24] 24.The method of claim 19, wherein the phase-shift and attenuation values are obtained by taking the logarithm of the ratio of the complex voltage signals obtained from the fitting expression at two azimuthal angles.

[c25] 25. The method of claim 24, wherein the two azimuthal angles are 0 and 180 degrees from a determined bedding azimuth.

[c26] 26.The method of claim 18, wherein the second antennas are symmetric with respect to the first antennas, and further comprising the steps of:
suspending rotation of the logging instrument;
determining the azimuth of a bed of interest by combining the first and second antenna couplings;
determining the constant and first harmonic coefficients from measured first and second voltage signals acquired when the instrument is not rotating;

using the constant coefficients to execute the fitting step when the logging instrument is rotating.

[c27] 27.The method of claim 26, further comprising the steps of:
updating the azimuthal variations of the measured first and second voltage signals; and
re-calculating equivalent voltages when the tool is in the plane of the bedding.

[c28] 28.The method of claim 19, wherein the phase-shift and attenuation values are obtained from log ((c0 + c1)/(c0 - c1)), where c0 and c1 are the complex fitting coefficients taking a determined bedding azimuth as an angle reference.

[c29] 29.The method of claim 7, wherein the iterative fitting algorithm includes the steps of:

$initialize\ P_0\ and\ U_0;$

$for\quad m = 1\quad to\quad Nsamples$

$$P_m \leftarrow P_{m-1} - \frac{P_{m-1} \cdot r_{m-1}^T \cdot r_{m-1} \cdot P_{m-1}}{1 + r_{m-1} \cdot P_{m-1} \cdot r_{m-1}^T}$$

$$U_m \leftarrow U_{m-1} - P_m \cdot r_{m-1}^T \cdot \left(y_{m-1} - U_{m-1}^T \cdot r_{m-1}^T\right)^T;$$

$next\quad m;$

$return(U);$

where:

$Nsamples$ is the total number of samples acquired in one cycle,
$M$ is the dimension of the approximate function vector (number of approximation functions),
U is the vector of fitting coefficients of dimension $M$,
$r$ is the vector of approximate function values at each measure position of dimension $M$, and
P is a matrix of dimension $M \times M$.

[c30] 30.The method of claim 29, wherein the iterative fitting algorithm determines if the fit error is below a pre-defined threshold, and if U converges to a value that is representative of the fitting coefficients.

[c31] 31.The method of claim 30, wherein the iterative fitting algorithm employs an integer implementation.

[c32] 32.The method of claim 29, further comprising the step of using the fitting coefficients to determine the orientation of a formation bed.

[c33] 33.The method of claim 32, wherein:
the measured first and second voltage signals are complex voltage signals; and

the orientation of the formation bed with respect to the azimuthal angle reference for each channel of directional measurement is determined according to:

$$\phi_{bed} = \tan^{-1}\left[\left|\frac{\tilde{C}_{1s}(\theta_T,\theta_R)}{\tilde{C}_{1c}(\theta_T,\theta_R)}\right|\right],$$

where $C_{1s}$ is the real or imaginary part of the coefficient of $sin\phi$, and $C_{1c}$ is the coefficient of $cos\phi$ from the fitting.

[c34] 34. The method of claim 33, further comprising the step of calculating a common azimuthal angle for the first and second voltage signals using weighted averaging of the fitting coefficients for real and imaginary parts of the measured voltage signals.

[c35] 35.The method of claim 34, further comprising the step of calculating the amplitude and phase of the measured voltage signal at an assumed normal direction to a bed boundary of interest.

[c36] 36.The method of claim 35, further comprising the step of determining phase shift and attenuation by taking propagation measurements for two azimuth angles.

[c37] 37.The method of claim 36, further comprising the application of an inversion technique to interpret the directional measurements.

[c38] 38.The method of claim 36, wherein the azimuth angles are

$\Phi_{bed}$ and $\Phi_{bed} + 180°$.

[c39] 39.The method of claim 36, further comprising the step of combining the signals from the fitting coefficients for the first and second voltage measurements, to produce signals necessary to determine the distance to bed boundaries of interest.

[c40] 40.A method for characterizing a subsurface formation, comprising the step of:
cross-plotting two directional logging measurements acquired from an instrument disposed in a borehole intersecting the formation to obtain a distance to at least one formation boundary and a resistivity for at least one formation bed.

[c41] 41. The method of claim 40, wherein:
the cross-plotting is achieved using a one-boundary model;
the obtained resistivity is the shoulder-bed resistivity; and
the obtained distance is the closest distance to the shoulder-bed.

[c42] 42.The method of claim 40, wherein the cross-plotting

step includes the steps of:
defining an appropriate model;
selecting appropriate directional measurements;
inputting the selected measurements to the defined model to generate the cross-plot; and
generating a visual representation of the cross-plot.

[c43] 43.The method of claim 42, further comprising the step of updating the cross-plot with further real-time measurements.

[c44] 44.The method of claim 43, further comprising the step of:
using cross-plot definitions and the real-time measurements to determine a resistivity for at least one formation bed and a distance to at least one formation boundary.

[c45] 45.The method of claim 40, wherein the obtained distance and resistivity are used to make drilling decisions.

[c46] 46.A method for characterizing a subsurface formation, comprising the step of:
cross-plotting a resistivity and a directional measurement determined using an instrument disposed in a borehole intersecting the formation to obtain a distance to at least one formation boundary and a resistivity for at

least one formation bed.

[c47] 47. The method of claim 46, wherein:
the cross-plotting is achieved using a one-boundary model;
the obtained resistivity is the shoulder-bed resistivity; and
the obtained distance is the closest distance to the shoulder-bed.

[c48] 48.A method for characterizing a subsurface formation, comprising the step of:
cross-plotting a resistivity and two directional measurements determined using an instrument disposed in a borehole intersecting the formation to obtain a distance to at least one formation boundary and a resistivity for at least two formation beds.

[c49] 49. The method of claim 48, wherein:
the cross-plotting is achieved using a one-boundary model;
the obtained resistivities are the bed and shoulder-bed resistivities; and
the obtained distance is the closest distance to the shoulder-bed.

[c50] 50.The method of claim 48, further comprising the steps

of:

selecting an appropriate inversion model for the selected real-time directional measurements;

verifying that the selected model is consistent with other information; and

using the verified model to make drilling decisions.

[c51] 51.The method of claim 50, wherein the model-selection step includes running at least one model-type selected from the set of:

homogenous isotropic (single parameter: resistivity);

homogenous anisotropic (two parameters: Rh and Rv);

single boundary isotropic formation, boundary above or below (three parameters: Rbed, Rshoulder and distance to boundary);

single boundary anisotropic formation, boundary above or below (four parameters: Rbed_h, Rbed_v, Rshoulder and distance to boundary);

two boundary isotropic formation three parameters: (five parameters: Rbed, Rshoulder_up, Rshoulder_down and distance to boundary above and below the tool); and

two boundary anisotropic formation three parameters: (six parameters: Rbed_h, Rbed_v, Rshoulder_up, Rshoulder_down and distance to boundary above and below the tool).

[c52] 52.The method of claim 50, wherein the model selection step includes creating a visualization of the selected directional measurements.

[c53] 53.The method of claim 50, wherein the model selection step includes use Akaike Information Criterion to penalize the model complexity.

[c54] 54.The method of claim 50, wherein the model selection step includes:
identifying known formation parameters;
interactively choosing the models with which to invert the selected directional measurements; and
selecting the simplest model that fits the known information.

[c55] 55.The method of claim 50, wherein the verifying step includes the step of:
comparing the selected model to known geological characteristics and other measured formation parameters.

[c56] 56.The method of claim 55, wherein the verifying step further includes the step of updating the selected model if the selected model is not consistent with the known information.

[c57] 57.The method of claim 56, wherein the updating step includes the steps of:

refining the selected model based upon one of trends, prior knowledge, external information, and a combination thereof;

selecting parameters to be inverted;

defining ranges for all parameters to be inverted;

updating the inversion model by adding more formation beds;

re-weighting or eliminating some of the selected real-time directional measurements; and

re-inverting the resulting real-time directional measurements to the updated model.

[c58] 58.An apparatus for measuring characteristics of earth formations surrounding a borehole, comprising:

a logging instrument adapted for disposal within the borehole, the logging instrument having a longitudinal axis and being equipped with first and second transmitter-receiver antenna pairs;

the first transmitter-receiver antenna pair comprising

a first transmitter antenna having a magnetic dipole oriented in a first direction with respect to the longitudinal axis of the logging instrument,

a first receiver antenna located a first distance away from the first transmitter antenna and having a magnetic dipole oriented in a second direction, the first and second directions being different,

the magnetic dipoles of the first transmitter and receiver antennas defining a plane that includes the longitudinal axis of the logging instrument,

the second transmitter-receiver antenna pair comprising a second transmitter antenna having a magnetic dipole oriented in the second direction with respect to the longitudinal axis of the logging instrument,

a second receiver antenna located the first distance away from the second transmitter antenna and having a magnetic dipole oriented in the first direction,

the magnetic dipoles of the second transmitter and receiver antennas defining a plane that includes the longitudinal axis of the logging instrument,

a toolface sensor for continuously indicating the azimuthal orientation of the logging instrument; and

a controller for controlling the first and second transmitter-receiver antennas pairs so as to selectively transmit electromagnetic energy into the formation and measure the voltage signals associated with the transmitted electromagnetic energy as a function of the azimuthal orientation of the logging instrument.

[c59] 59.The apparatus of claim 58, wherein the second transmitter-receiver antenna pairs are oriented at a first azimuthal angle with respect to the first transmitter-receiver antenna pairs about the longitudinal axis of the

logging instrument.

[c60] 60.The apparatus of claim 58, further comprising:
a CPU for processing the measured voltage signals within the borehole;
a telemetry apparatus for transmitting the measured signals and CPU-processed results from the borehole to the surface; and
a surface system for further processing measured signals together with other measurements to generate and display selected parameters of a consistent earth model.

[c61] 61.The apparatus of claim 58, wherein the formation characteristic is resistivity.

[c62] 62.The apparatus of claim 58, wherein the formation characteristic is the geometry information of the earth, including the dip, azimuth, and bed thickness.

[c63] 63.The apparatus of claim 58, wherein the first direction is substantially collinear with the longitudinal axis of the logging instrument.

[c64] 64.The apparatus of claim 58, wherein the second direction is substantially collinear with the longitudinal axis of the logging instrument.

[c65] 65.The apparatus of claim 58, wherein the first direction

is substantially 45 degrees from the longitudinal axis of the logging instrument.

[c66] 66.The apparatus of claim 58, wherein the second direction is substantially 45 degrees from the longitudinal axis of the logging instrument.

[c67] 67.The apparatus of claim 58, wherein each of the transmitters and receivers have transceiver capabilities.

[c68] 68.The apparatus of claim 59, wherein the first azimuthal angle is substantially 90 degrees.

[c69] 69.The apparatus of claim 58, wherein the first and second transmitter-receiver antenna pairs are located at the same physical positions on the logging instrument.

[c70] 70.The apparatus of claim 58, wherein the toolface sensor employs magnetometers to indicate the azimuthal orientation of the logging instrument with respect to earth"s magnetic north.

[c71] 71.The apparatus of claim 58, where the toolface sensor employs gravitation sensors to indicate the azimuthal orientation of the logging instrument with respect to the earth"s gravity vector.